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Chapter

Plant Growth and Morphophysiological Modifications in Perennial Ryegrass under Environmental Stress

Fuchun Xie, Rahul Datta and Dong Qin

Abstract

Perennial ryegrass (*Lolium perenne* L.) is a popular and important cool-season turfgrass used in parks, landscapes, sports fields, and golf courses, and it has significant ecological, environmental, and economic values. It is also widely used as forage and pasture grass for animals around the world. However, the growth of perennial ryegrass is often affected by various abiotic stresses, which cause declines in turf quality and forage production. Among abiotic stresses, drought, salinity, temperature, and heavy metal are the most detrimental factors for perennial ryegrass growth in different regions, which result in growth inhibition, cell structure damage, and metabolic dysfunction. Many researches have revealed a lot useful information for understanding the mechanism of tolerance to adverse stresses at morphophysiological level. In this chapter, we will give a systematic literature review about morphological and physiological changes of perennial ryegrass in response to main stress factors and provide detail aspects of improving perennial ryegrass resistance based on research progress. Understanding morphophysiological response in perennial ryegrass under stress will contribute to improving further insights on fundamental mechanisms of perennial ryegrass stress tolerance and providing valuable information for breeding resistance cultivars of perennial ryegrass.

Keywords: perennial ryegrass, morphology, physiology, abiotic stress, stress resistance

1. Introduction

Urban green areas have important various functions contributing to the quality of human health. Well-kept lawns enhance the esthetic value of the entire city and are involved in phytoremediation, leading to an improvement in the quality of the air and soil [1–4]. Perennial ryegrass (*Lolium perenne* L.) is an important and widespread perennial cool-season grass cultivated in temperate climates, originating in Europe, temperate Asia, and North Africa [5]. Perennial ryegrass is commonly used in home lawns, sport fields, and parks with rapid growth and establishing rate, and other elements for ecosystem service due to its massive root system, superior regeneration, and tillering ability. It is also widely used as nutritive forage and pasture grass for animals around the world [6–8]. Moreover, numerous perennial ryegrass genotypes and hybrids are now released by commercial utilities [9, 10].

In fields, the growth and development process of plants needs to counteract various environmental stresses such as salinity, drought, cold, heat, and heavy metal [11–13]. Harsh environmental conditions may result in growth inhibition, cell structure damage, and metabolic dysfunction [14–20]. Moreover, stresses will further be intensified for the potential impact of climate change in future. Thus, maintaining proper growth of turfgrass with minimal inputs under abiotic stress conditions is a great challenge for turfgrass industry. This challenge could be addressed through improving the stress tolerance of turfgrass [14, 21]. Understanding morphological and physiological mechanisms of turfgrass adaptation to various abiotic stresses is a key step for the development of stress-tolerant ability and cost-effective and efficient management practices [13]. Morphophysiological mechanisms of turfgrass in abiotic stresses tolerance involve phenotypic changes, multiple physiological and biochemical response, and complex metabolic processes, such as water and nutrient relations, carbohydrate metabolism, protein metabolism, hormone metabolism, as well as antioxidant defenses [22, 23]. Current studies on morphophysiological mechanism controlling turfgrass adaptations to various growth conditions have provided important information for production of abiotic stress-tolerant germplasms and the further understanding of regulation mechanism of turfgrass response to abiotic stresses [13, 24, 25]. However, the mechanisms of the adaptive responses are integrated but are not necessarily the same [14]; thus, studies on how perennial ryegrass adapts to stress conditions will become more important with the increasing pressure of utilizing both ecological and economical strategies in the turf management. Furthermore, insights into mechanisms of stress resistance in perennial ryegrass will aid in identifying important characteristics for selecting the criteria of improving stress tolerance and will ultimately lead to better selection of new cultivars adapted to adverse environments. This chapter, therefore, focuses on an extensive overview of the current understanding of changes in physiology and growth/development of perennial ryegrass under various abiotic stresses. In addition, strategies for improving the stress tolerance of perennial ryegrass are also presented. This review can contribute to the better understanding of the mechanisms of perennial ryegrass response to environmental stresses and can provide valuable information for improving resistance characteristics of perennial ryegrass by breeding. Moreover, enhancing our understanding of physiological effects of abiotic stresses can provide guidelines for the practical management strategies of the maintenance of high-quality turf under limited resource availability.

2. Abiotic stresses

Abiotic stresses are major environmental conditions that reduce plant growth, productivity, and quality. Plants have evolved mechanisms to perceive these environmental challenges, transmit the stress signals within cells as well as between cells and tissues, and make appropriate adjustments in their growth and development for survive and reproduce [26–29]. The morphological and physiological changes of perennial ryegrass under abiotic stress will be discussed in this chapter.

2.1 Responses of drought stress in perennial ryegrass

Growth and development processes are inhibited when plant is exposed to drought stress [30–36]. Morphological adjustments, such as biomass allocation and leave changes, have been proposed as the key mechanisms used by turfgrass to enhance survival under drought [37]. There is a series of morphology changes in perennial ryegrass under drought stress. Drought stress reduced the turf quality (TQ), number of live tillers and dry-matter yield [38–40]. Moreover, drought significantly enhanced root to shoot ratio (R/S) in perennial ryegrass to an less extents, depending on the intensity, the reason may be that perennial ryegrass in drought stress develop a large R/S to maintain water and nutrient uptake [39]. The leaves of perennial ryegrass under drought stress were also dramatically different from that of nonstressed perennial ryegrass, for example, under drought stress, the diurnal variation in the rate of leaf extension was smaller but the leaves tended to grow faster at night compared to normal irrigation controls; however, water stress ultimately reduced the rate of leaf extension and leaf area in perennial ryegrass [40]. Furthermore, the leaves' epidermis of perennial ryegrass under drought reduced the stomatal size and increased the numbers per unit leaf area. Drought also resulted deeper ridging on leaf ad-axial surface, smaller epidermal cells and bigger ridge angle [40]. Under drought stress, leave stomata of perennial ryegrass began to close to reduce their evapotranspiration rate (ET), at leaf water potentials below—13 bars [40].

Drought stress causes significant physiological changes, including photosynthesis, osmotic adjustment substances, proteins, and antioxidant metabolism, in perennial ryegrass. For instance, the content of leaf total nitrogen and leaf relative water content (RWC) were tested to decrease, on the contrary, antioxidant activity including ascorbate peroxidase (APX), superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GR), glutathione S-transferase (GST), amino acids such as aspartic acid, threonine, serine, glutamic acid, abscisic acid (ABA) concentration, and proline content increased under drought stress [41]. Photosynthesis is the primary process controlling plant growth and adaption to drought stress [42]. The canopy photosynthesis of perennial ryegrass at saturating light intensity was reduced by about half in the stressed field swards and by more than 80% in the stressed simulated swards [38]. Drought stress inhibits photosynthesis, which may be the result of low CO_2 availability caused by stomatal closure and/or the inhibition of photochemical reactions and carbon assimilation metabolism [43]. In addition to the photosynthesis, starchis also considered as a buffer for imbalance between acquisition by photosynthesis and C-sink activities such as growth and respiration resulted from drought, also stress due to the excessive use of inorganic fertilizer [44]. However, use of green manure also has risk of xenobiotic contamination [45–47], and the soluble sugars, including sucrose, fructose and glucose, are involved in multiple physiological functions such as respiration, turgor maintenance, signaling and defense. Under drought conditions, starch of perennial ryegrass significantly decreased in shoots, but did not change in roots, which indicated that perennial ryegrass in drought condition preferentially allocates carbon not only to root growth, but also to root storage, while soluble sugars were enhanced in both shoots and roots. Accumulation of soluble sugars has been widely reported for plants upon water stress as a means to provide osmotic protection [39], which suggested that increasing of soluble sugars was benefit to plants to maintain growth and active metabolic activities under water deficit.

It is generally accepted that there is a noticeable genotypic variation in perennial ryegrass for drought stress responses. The research showed that one self-pollinating genotype "S10" showed higher RWC, shoot dry weight (SDW), proline, ABA, nitrogen and amino acid contents, and antioxidant enzymes activities in comparison with two commercial genotypes of "Vigor" and "Speedy" [41]. Proteins involved in carbon and energy metabolism, photosynthesis, tricarboxylic acid cycle (TCA) cycle, redox, and transport categories were upregulated in the two commercial genotypes of "Vigo" and "Speedy," while the protein profile of the "S10" changed slightly under drought stress, and the reason may be that self-pollination in the genetic background of the "S10" genotype may have a lower variation in response to drought stress conditions [41]. Additionally, other research indicated that tetraploid perennial ryegrass exhibited a greater biomass under severe drought, whereas diploids had a greater biomass under the current rainfall [48, 49]. Moreover, tetraploid perennial ryegrass populations were able to develop more shoot and root dry matter than diploid populations in following the application of drought stress [50].

The above researches showed that drought stress caused significantly physiological and morphological changes in perennial ryegrass (**Table 1**) [55, 56]. Thus, the growth of perennial ryegrass is severely restricted by soil water deficits [57]. Increasing drought tolerance of perennial ryegrass via strategies is importance for both water conservation and maintaining growth in water limiting environments. For example, the grass-Epichloë endophytic improved water utilization and drought tolerance in perennial ryegrass [58]. Moreover, arbuscular mycorrhizal fungi (AMF) + Epichloë treatments increased phosphorus (P) uptake, net photosynthetic rate (Pn), root activity, soluble sugar concentration, peroxidase (POD) activity, and decreased malonyldialdehyde (MDA) concentration in perennial ryegrass under drought stress, the reason may be that Plant-AMF-Epichloë symbiosis alleviated the damage caused by drought stress by promoting P uptake, photosynthesis, and the accumulation of osmoregulatory substances [59]. Additionally, application of plant growth regulators (PGRs) have been reported to be a promising way of reducing drought stress impacts [60]. The study manifested that trinexapac ethyl (TE) treatment increased chlorophyll content, proline content, the RWC, soluble sugar content, antioxidant enzymes activities, decreased MDA and hydrogen peroxide (H_2O_2) contents in perennial ryegrass under drought stress, while Paclobutrazol (PAC)- and ABA-treated perennial ryegrasses were all effective in mitigating physiological damages resulting from drought stress [52]. Furthermore, overexpression of some drought-related genes has been shown to effectively improve drought tolerance of plants [61]. According to Patel et al. [53], overexpression of *LpHUB1* gene conferred drought tolerance in perennial ryegrass.

2.2 Responses of temperature stress in perennial ryegrass

Perennial ryegrass can grow throughout the year, and the major constraint on growth is temperature [51, 62]. Perennial ryegrass has an optimal growth temperature of about 20°C, and it is sensitive to high (30–40°C) and low (−20 to 0°C) temperatures [63, 64]. Common perennial ryegrass germinates quickly and can be used as a temporary ground cover while the slower growing bluegrass plants take

Morphological responses	Physiological responses	Strategies
• Decreased turf quality • Enhanced R/S • Decreased leaf area • Reduce the number of live tillers • Had smaller stomata and epidermal cells • Had bigger ridge angle • Controlled stomatal opening [38–40]	• Decline biomass • Decline photosynthetic rate • Increased osmotic adjustment substances • Increased antioxidant activity • Increased amino acid content [39, 41, 51]	• Application of plant growth regulators (PGRs) • Selected drought resistance cultivars from different cultivars • Using endophytes • Using transgenic technology [52–54]

Table 1.
Morphophysiological response of perennial ryegrass under drought stress.

hold in cool temperate region. In warm climates, it is used as an overseed to maintain winter green in the lawn after the warm season grasses go dormant. However, populations of perennial ryegrass will not survive the summer heat. Severe heat stress (40/35°C day/night) caused significant physiological damages, including declining in TQ, RWC, CAT activity, and enhancing in electrolyte leakage (EL) of leaves and MDA content, in perennial ryegrass [65]. Moreover, heat stress decreased plant height (HT), leaf fresh weight (LFW) and leaf fresh dry (LFD), and increased cytokinin and auxin at 35/30°C (day/night) of temperature [66]. Moreover, low temperature is one of the main factors that limit the persistence of perennial ryegrass-dominated grasslands in northern regions. Cold stress decreased TQ, regrowth, dry weight, and tiller density in perennial ryegrass when the winters were mild with short (2–6 weeks) periods of lower than −10°C temperatures and no permanent snow cover [67]. Furthermore, cold stress decreased RWC and increase EL in leaves and roots when perennial ryegrass was exposed to −15 or −25°C [68]. To resolve these problems and maintain high visual quality of perennial ryegrass through the year, it is important to found new cultivars to adapt to temperature stress. Variations of heat- or cold- resistance were also found among different perennial ryegrass cultivars. Thus, selection cold- or heat-tolerant cultivars during perennial ryegrass genotypes can be an effective method for temperature tolerance improvement in perennial ryegrass. The research tested the heat tolerance of 58 cultivars collected from seed companies and research centers in U.S.A., New Zealand, and Europe, the result showed that distinct heat tolerance was found among the cultivars at all the temperature regimes, and the least and most tolerant cultivars were "JPR005" and "JPR178," respectively [69]. The other research indicated that changes of morphology and physiology were different for heat-tolerant accession "PI265351" and sensitive accession "PI225825" [66]. Similarly, the heat-tolerant populations of perennial grass showed significantly lower degree damage in efficiency of photosystem II and cell membrane stability than the sensitive ones at different levels of stress [70]. Additionally, the study showed that 21 accessions sampled from a larger set of 300 accessions with known winter hardiness, the result showed that the degree of semi-lethal temperature in 21 ryegrass varieties varies from −10.31 to −13.95°C, with 3 accessions possessing significantly greater freezing tolerance than the most freeze-tolerant check "NK200" [71]. Moreover, tetraploid genotypes of perennial ryegrass demonstrated higher tolerance to cold stress conditions, better spring growth, and regrowth after cuts, and higher dry matter yield compared to diploid genotypes [67].

The studies indicate that temperature stress caused the morphological and physiological damage in plant, and the response of genotypes to temperature stress was different [72–80]. Therefore, founding some strategies which could improve cold- or heat-tolerant of perennial ryegrass is important. It was also reported that 24-epibrassinolide promoted carbohydrates accumulation in crowns of perennial ryegrass during cold acclimation by regulation of gene expression and enzyme activities, and which resulted in increased frost tolerance [81]. Moreover, drought preconditioning increased in crown fructans, proline, and total soluble protein content for "Buccaneer" and "Sunkissed" during cold acclimation, which suggested a synergistic effect between drought exposure and low temperature, and drought preconditioning resulted in an improvement in freezing tolerance of perennial ryegrass [82]. Additionally, previous studies have shown that the enzyme activity level and gene expression of antioxidants are associated with cold and heat tolerance in a cool-season perennial grass species [83, 84]. For instance, *LpHOX21* was positively associated with heat tolerance of perennial ryegrass [85]. Similarly, P450 gene (*LpCYP72A161*) showed remarkable upregulation in perennial ryegrass under heat and cold treatment. Therefore, transferring key genes into perennial ryegrass will be beneficial to improve heat or freezing tolerance [86].

2.3 Responses of salt stress in perennial ryegrass

Salinity stress has become a more significant problem in turfgrass management in many areas [13]. Responses of plants to salinity stress occur mainly through two distinct phases over time: osmotic-changing and ion specific phases [87–89]. Like other turfgrasses, salt stress caused morphology, physiology, molecular changes in growth and development of perennial ryegrass, such as TQ LFW, LED, and RWC of perennial ryegrass decreasing after exposure to salinity [89, 90]. The alterations of morphological characteristics of turfgrass under salt stress are derived from the changes of physiological traits such as cell membrane stability [14]. It was reported that MDA content and EL enhanced by NaCl concentration in perennial ryegrass [54]. Simultaneously, superoxide radical (O^{2-}), H_2O_2, and singlet oxygen (O_2) concentration increased observably in perennial ryegrass after salt stress treatment [54, 91]. To scavenge reactive oxygen species (ROS), salt-stressed leaves of perennial ryegrass exhibited greater activities of SOD, APX, and CAT at the initial stage of salt stress, but lower levels of enzyme with the extension of salt stress [89]. Salt stress also negatively affected on the total chlorophyll (Chl), Chl a and Chl b, in perennial ryegrass [89], which showed that salt stress induced Chl decomposition in leaves. Moreover, a further research of PSII changes in perennial ryegrass discovered that quantum yields, efficiencies, and energy fluxes were impacted after salt stress treatment [92, 93]. Additionally, a vast amount of Na^+ accumulated in plants could induce ionic imbalance in the cells. It was reported that Na^+ concentration accumulated rapidly and other ion concentrations including K^+, Ca^{2+} and Mg^{2+} were decreased in response to salt stress in perennial ryegrass [89].

Salt stress causes dramatically changes in morphology and physiology of perennial ryegrass as showed above and summaries in **Figure 1**. However, these responses varied greatly among different genotypes. The research compared the salt tolerance in 10 accessions of perennial ryegrass, and determined that “PI275660”

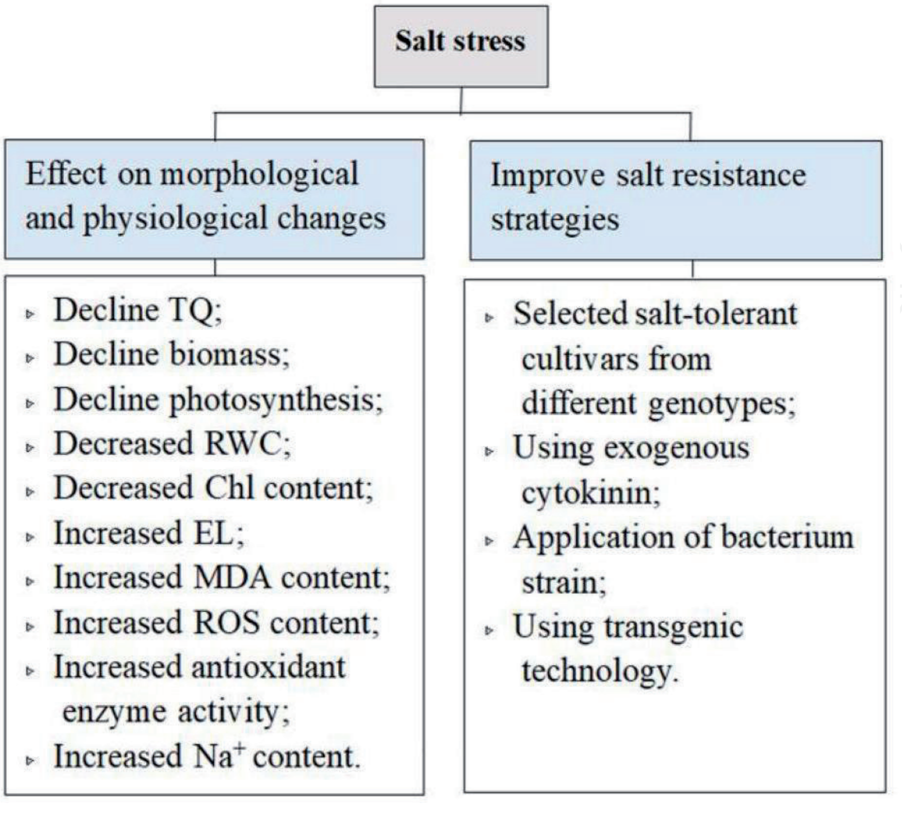

Figure 1.
Morphophysiological response and strategies for salt stress in perennial ryegrass.

and "BrightStar" showed the best tolerance to salt stress, while "PI231595" and "PI251141" were the most sensitive accessions [5]. The other research reported that the effect on parameters of photosynthetic efficiency in perennial ryegrass "Roadrunner" was less than that in "Nira" under salt stress condition [6]. Moreover, the highest salt tolerance accessions were from the European group, wild accessions and exhibited more variation in functional traits and salt tolerance than commercial cultivars [90]. Some other strategies can also improve the salt-tolerance in perennial ryegrass. Salt-tolerant transgenic perennial ryegrass could be obtained by *Agrobacterium tumefaciens*-mediated transformation of the vacuolar Na^+/H^+ antiporter gene [94]. Additionally, exogenous cytokinin applications alleviated salt-induced leaf senescence in perennial ryegrass [8]. Furthermore, salt tolerance of perennial ryegrass can increase by a novel bacterium strain from the rhizosphere of a desert shrub *Haloxylon ammodendron* induced [95].

2.4 Responses of heavy metals stress in perennial ryegrass

The continuing industrialization has led to extensive environmental problems worldwide [96–98]. Heavy metals produced from industry are released to soil. Thus, high accumulation of heavy metal in soil can induce environmental stress on plants [14]. Research on the response of perennial ryegrass to heavy metal stress has also progressed in recent years. It has been proved that heavy metals can induce damage and affect metabolic processes in perennial ryegrass [98–100]. For example, perennial ryegrass had characters in yield reduction and visible symptoms of phytotoxicity under cadmium (Cd) and zinc (Zn) stress [98]. Moreover, the cellular membrane system was damaged because of elevated MDA and EL contents when perennial ryegrass was exposed to salt condition [101]. According to studies, a dramatic inhibition of root and shoot growth was detected in perennial ryegrass after heavy metals treatment [101–103]. Moreover, the composition of the leaves of perennial ryegrass, including apparently opposite effects on the calcium (Ca), potassium (K) and P levels, was changed under the aluminum (Al) stress [104]. Additionally, ROS bursts occurred in perennial ryegrass under heavy mental stress conditions. For instance, H_2O_2 and O^{2-} were significantly accumulated in perennial ryegrass under Cd stress [105]. Hence, the protection mechanisms in perennial ryegrass such as the antioxidant system were triggered under heavy stress, resulting in the increase of SOD, CAT, and POD activities and their corresponding genes [106]. Moreover, content of fructan, sugar, and starch showed an increasing trend in perennial ryegrass after heavy metal stress [98]. However, certain concentrations of heavy metal were beneficial for the growth of perennial ryegrass [107]. Heavy metal stresses not only induce physiological damage, but also inhibit germination and growth of perennial ryegrass [108].

To improve the heavy metal stress tolerance of perennial ryegrass, several investigations were conducted in recent years. It was reported that signal messengers such as nitricoxide (NO) and glycine betaine (GB) play crucial roles in alleviating Cd and Cu-induced damages in perennial ryegrass [109, 110]. Moreover, the exogenous P was testified to improve the Cd tolerance of perennial ryegrass, the reason may be that exogenous P facilitates chelation-mediated Cd detoxification processes [105]. Similarly, a high dose of P amendment alleviated Mn-toxicity in Mn-sensitive genotype in perennial ryegrass [102]. Furthermore, the addition of biochar to a contaminated mine soil improved the nutrient status of this mine soil and contributed to a better establishment of perennial ryegrass [100]. Additionally, AMF enhance both absorption and stabilization of Cd by perennial ryegrass in a Cd-contaminated acidic soil [96], and ethylene diamine tetra acetate (EDTA) enhanced phytoremediation of heavy metals from municipal waste compost and sludge soil by perennial ryegrass [99, 111, 112].

3. Conclusions and future research perspectives

Significant progress has been made in the understanding of morphological and physiological mechanisms associated with perennial ryegrass tolerance to drought, salinity, temperature, and heavy mental stresses. Harsh stress conditions inhibit the growth and development and decrease TQ, root length, and dry weight in perennial ryegrass. Moreover, physiological response to abiotic stress in perennial ryegrass displays changes of the cell membrane, photosystem, metabolites, and antioxidant system. The contents of MDA and EL are increased, while Chl content and photosynthesis are decreased under stress conditions. To regulate the osmotic potential of the cell after stress treatment, some metabolites such as proline, soluble sugars, and proteins accumulate. Meanwhile, antioxidant enzymes' activities increase in perennial ryegrass for scavenging ROS. Perennial ryegrass has protective responses against unfavorable conditions, but there is a threshold to these physiological changes. To understand the response to abiotic stress and resistance attributes in perennial ryegrass will be beneficial to breeding in future.

For improving the stress tolerance of perennial ryegrass, some practical strategies are exploited currently, such as application of phytohormones, endophytes, and chemical compounds. Further research on increasing perennial ryegrass stress tolerance should pay more attention to transgenic technology to identify effective genes for modifying stress-tolerance ability.

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References

[1] Dabrowski P, Kalaji MH, Baczewska AH, Pawluśkiewicz B, Mastalerczuk G, Borawska-Jarmulowicz B, et al. Delayed chlorophyll a fluorescence, MR 820, and gas exchange changes in perennial ryegrass under salt stress. Journal of Luminescence. 2017;**183**:322-333. DOI: 10.1016/j.jlumin.2016.11.031

[2] Hafiz MH, Muhammad A, Farhat A, Hafiz FB, Saeed AQ, Muhammad M, et al. Environmental factors affecting the frequency of road traffic accidents: A case study of sub-urban area of Pakistan. Environmental Science and Pollution Research. 2019. DOI: 10.1007/s11356-019-04752-8

[3] Sajjad H, Muhammad M, Ashfaq A, Waseem A, Hafiz MH, Mazhar A, et al. Using GIS tools to detect the land use/land cover changes during forty years in Lodhran district of Pakistan. Environmental Science and Pollution Research. 2019. DOI: 10.1007/s11356-019-06072-3

[4] Adnan M, Zahir S, Fahad S, Arif M, Mukhtar A, Imtiaz AK, et al. Phosphate-solubilizing bacteria nullify the antagonistic effect of soil calcification on bioavailability of phosphorus in alkaline soils. Scientific Reports. 2018;**8**:4339. DOI: 10.1038/s41598-018-22653-7

[5] Tang J, Camberato JJ, Yu X, Luo N, Bian S, Jiang Y. Growth response, carbohydrate and ion accumulation of diverse perennial ryegrass accessions to increasing salinity. Scientia Horticulturae. 2013;**154**:73-81. DOI: 10.1016/j.scienta.2013.02.021

[6] Yu X, Bai G, Liu S, Luo N, Wang Y, Richmond DS, et al. Association of candidate genes with drought tolerance traits in diverse perennial ryegrass accessions. Journal of Experimental Botany. 2013;**64**:1537-1551. DOI: 10.1093/jxb/ert018

[7] Yu X, Pijut PM, Byrne S, Asp T, Bai G, Jiang Y. Candidate gene association mapping for winter survival and spring regrowth in perennial ryegrass. Plant Science. 2015;**235**:37-45. DOI: 10.1016/j.plantsci.2015.03.003

[8] Ma X, Zhang J, Huang B. Cytokinin-mitigation of salt-induced leaf senescence in perennial ryegrass involving the activation of antioxidant systems and ionic balance. Environmental and Experimental Botany. 2016;**125**:1-11. DOI: 10.1016/j.envexpbot.2016.01.002

[9] Dabrowski P, Pawluśkiewicz B, Kalaji HM, Baczewska AH. The effect of light availability on leaf area index, biomass production and plant species composition of park grasslands in Warsaw. Plant, Soil and Environment. 2013;**59**:543-548. DOI: 10.17221/140/2013-PSE

[10] Dabrowski P, Pawluśkiewicz B, Baczewska AH, Oglecki P, Kalaji H. Chlorophyll a fluorescence of perennial ryegrass (*Lolium perenne* L.) varieties under long term exposure to shade. Zemdirbyste-Agriculture. 2015;**102**:305-312. DOI: 10.13080/z-a.2015.102.039

[11] Shah S, Li X, Chen YJ, Zhang L, Fahad S, Hussain S, et al. Silicon application increases drought tolerance of Kentucky bluegrass by improving plant water relations and morphophysiological functions. The Scientific World Journal. 2014. DOI: 10.1155/2014/368694

[12] Muhammad Z, Abdul MK, Abdul MS, Kenneth BM, Muhammad S, Shahen S, et al. Performance of *Aeluropus lagopoides* (mangrove grass) ecotypes, a potential turfgrass, under high saline conditions. Environmental Science and Pollution Research. 2019. DOI: 10.1007/s11356-019-04838-3

[13] Huang B, DaCosta M, Jiang Y. Research advances in mechanisms of turfgrass tolerance to abiotic stresses: From physiology to molecular biology. Critical Reviews in Plant Sciences. 2014;**33**:141-189. DOI: 10.1080/07352689.2014.870411

[14] Fan J, Zhang W, Amombo E, Hu L, Kjorven JO, Chen L. Mechanisms of environmental stress tolerance in turfgrass. Agronomy. 2020;**10**:522. DOI: 10.3390/agronomy10040522

[15] Hafiz MH, Wajid F, Farhat A, Fahad S, Shafqat S, Wajid N, et al. Maize plant nitrogen uptake dynamics at limited irrigation water and nitrogen. Environmental Science and Pollution Research. 2016;**24**(3):2549-2557. DOI: 10.1007/s11356-016-8031-0

[16] Nasim W, Ahmad A, Amin A, Tariq M, Awais M, Saqib M, et al. Radiation efficiency and nitrogen fertilizer impacts on sunflower crop in contrasting environments of Punjab. Pakistan Environmental Science and Pollution Research. 2017;**25**:1822-1836. DOI: 10.1007/s11356-017-0592-z

[17] Aziz K, Daniel KYT, Fazal M, Muhammad ZA, Farooq S, Fan W, et al. Nitrogen nutrition in cotton and control strategies for greenhouse gas emissions: A review. Environmental Science and Pollution Research. 2017;**24**:23471-23487. DOI: 10.1007/s11356-017-0131-y

[18] Aziz K, Daniel KYT, Muhammad ZA, Honghai L, Shahbaz AT, Mir A, et al. Nitrogen fertility and abiotic stresses management in cotton crop: A review. Environmental Science and Pollution Research. 2017;**24**:14551-14566. DOI: 10.1007/s11356-017-8920-x

[19] Hussain MA, Fahad S, Rahat S, Muhammad FJ, Muhammad M, Qasid A, et al. Multifunctional role of brassinosteroid and its analogues in plants. Plant Growth Regulation. 2020. DOI: 10.1007/s10725-020-00647-8

[20] Kamarn M, Wenwen C, Irshad A, Xiangping M, Xudong Z, Wennan S, et al. Effect of paclobutrazol, a potential growth regulator on stalk mechanical strength, lignin accumulation and its relation with lodging resistance of maize. Plant Growth Regulation. 2017;**84**:317-332. DOI: 10.1007/s10725-017-0342-8

[21] Huang S, Jiang S, Liang J, Chen M, Shi Y. Current knowledge of bermudagrass responses to abiotic stresses. Breeding Science. 2019;**69**: 215-226. DOI: 10.1270/jsbbs.18164

[22] Saud S, Chen Y, Fahad S, Hussain S, Na L, Xin L, et al. Silicate application increases the photosynthesis and its associated metabolic activities in Kentucky bluegrass under drought stress and post-drought recovery. Environmental Science and Pollution Research. 2016;**23**(17):17647-17655. DOI: 10.1007/s11356-016-6957-x

[23] Chen Y, Pettersen T, Kvalbein A, Aamlid TS. Playing quality, growth rate, thatch accumulation and tolerance to moss and annual bluegrass invasion as influenced by irrigation strategies on red fescue putting greens. Journal of Agronomy and Crop Science. 2018;**204**:185-195. DOI: 10.1111/jac.12246

[24] Saud S, Chen Y, Long B, Fahad S, Sadiq A. The different impact on the growth of cool season turf grass under the various conditions on salinity and drought stress. International Journal of Agricultural Science and Research. 2013;**3**:77-84

[25] Saud S, Fahad S, Cui G, Chen Y, Anwar S. Determining nitrogen isotopes discrimination under drought stress on enzymatic activities, nitrogen isotope abundance and water contents of Kentucky bluegrass. Scientific

Reports. 2020;**10**:6415. DOI: 10.1038/s41598-020-63548-w

[26] Gong Z, Xiong L, Shi H, Yang S, Herrera-Estrella LR, Xu G, et al. Plant abiotic stress response and nutrient use efficiency. Science China. Life Sciences. 2020;**63**:635-674. DOI: 10.1007/s11427-020-1683-x

[27] Akram R, Turan V, Hammad HM, Ahmad S, Hussain S, Hasnain A, et al. . In: Hashmi MZ, Varma A, editors. Fate of Organic and Inorganic Pollutants in Paddy Soils. Cham, Switzerland; 2018. pp. 197-214

[28] Akram R, Turan V, Wahid A, Ijaz M, Shahid MA, Kaleem S, et al. Paddy land pollutants and their role in climate change. In: Hashmi MZ, Varma A, editors. Environmental Pollution of Paddy Soils, Soil Biology. Cham, Switzerland: Springer International Publishing AG; 2018. pp. 113-124

[29] Depeng W, Fahad S, Saud S, Muhammad K, Aziz K, Mohammad NK, et al. Morphological acclimation to agronomic manipulation in leaf dispersion and orientation to promote "Ideotype" breeding: Evidence from 3D visual modeling of "super" rice (*Oryza sativa* L.). Plant Physiology and Biochemistry. 2018. DOI: 10.1016/j.plaphy.2018.11.010

[30] Fahad S, Chen Y, Saud S, Wang K, Xiong D, Chen C, et al. Ultraviolet radiation effect on photosynthetic pigments, biochemical attributes, antioxidant enzyme activity and hormonal contents of wheat. Journal of Food, Agriculture and Environment. 2013;**11**(3&4):1635-1641

[31] Fahad S, Hussain S, Bano A, Saud S, Hassan S, Shan D, et al. Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses: Consequences for changing environment. Environmental Science and Pollution Research. 2014;**22**(7):4907-4921. DOI: 10.1007/s11356-014-3754-2

[32] Fahad S, Nie L, Chen Y, Wu C, Xiong D, Saud S, et al. Crop plant hormones and environmental stress. Sustainable Agriculture Reviews. 2015b;**15**:371-400

[33] Zahida Z, Hafiz FB, Zulfiqar AS, Ghulam MS, Fahad S, Muhammad RA, et al. Effect of water management and silicon on germination, growth, phosphorus and arsenic uptake in rice. Ecotoxicology and Environmental Safety. 2017;**144**:11-18

[34] Hesham FA, Fahad S. Melatonin application enhances biochar efficiency for drought tolerance in maize varieties: Modifications in physio-biochemical machinery. Agronomy Journal. 2020:1-22

[35] Habib ur Rahman M, Ashfaq A, Aftab W, Manzoor H, Fahd R, Wajid I, et al. Application of CSM-CROPGRO-Cotton model for cultivars and optimum planting dates: Evaluation in changing semi-arid climate. Field Crops Research. 2017. DOI: 10.1016/j.fcr.2017.07.007

[36] Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A, et al. Crop production under drought and heat stress: Plant responses and management options. Frontiers in Plant Science. 2017;**8**:1147. DOI: 10.3389/fpls.2017.01147

[37] Saud S, Fahad S, Yajun C, Ihsan MZ, Hammad HM, Nasim W, et al. Effects of nitrogen supply on water stress and recovery mechanisms in Kentucky bluegrass plants. Frontiers in Plant Science. 2017;**8**:983. DOI: 10.3389/fpls.2017.00983

[38] Jones MB, Leafe EL, Stiles W. Water stress in field-grown perennial ryegrass. I. Its effect on growth, canopy

photosynthesis and transpiration. Association of Applied Biologists. 1980a;**96**:87-101. DOI: 10.1111/j.1744-7348.1980.Tb04772.x

[39] Guo T, Tian C, Chen C, Duan Z, Zhu Q, Sun L. Growth and carbohydrate dynamic of perennial ryegrass seedlings during PEG-simulated drought and subsequent recovery. Plant Physiology and Biochemistry. 2020;**154**:85-93. DOI: 10.1016/j.plaphy.2020.06.008

[40] Jones MB, Leafe EL, Stiles W. Water stress in field-grown perennial ryegrass. II. Its effect on leaf water status, stomatal resistance and leaf morphology. Association of Applied Biologists. 1980b;**96**:103-110. DOI: 10.1111/j.1744-7348.1980.tb04773.x

[41] Vanani FR, Shabani L, Sabzalian MR, Dehghanian F, Winner L. Comparative physiological and proteomic analysis indicates lower shock response to drought stress conditions in a self-pollinating perennial ryegrass. PLoS One. 2020;**15**(6):e0234317. DOI: 10.1371/journal.pone.0234317

[42] Bray EA. Physiology of plants under stress: Abiotic factors. Field Crops Research. 1998;**55**:192-193. DOI: 10.1016/s0378-4290(97)00069-5

[43] Lawlor DW, Cornic G. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. Plant, Cell & Environment. 2002;**25**:275-294. DOI: 10.1046/j.0016-8025.2001.00814.x

[44] Meena R, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, et al. Impact of agrochemicals on soil microbiota and management: A review. Land. 2020;**9**(2):34. DOI: 10.3390/land9020034

[45] Molaei A, Lakzian A, Haghnia G, Astaraei A, Rasouli-Sadaghiani M, Teresa Ceccherini M, et al. Assessment of some cultural experimental methods to study the effects of antibiotics on microbial activities in a soil: An incubation study. PLoS One. 2017;**12**(7):e0180663

[46] Datta R, Baraniya D, Wang Y-F, Kelkar A, Meena RS, Yadav GS, et al. Amino acid: Its dual role as nutrient and scavenger of free radicals in soil. Sustainability. 2017;**9**(8):1402

[47] Molaei A, Lakzian A, Datta R, Haghnia G, Astaraei A, Rasouli-Sadaghiani M, et al. Impact of chlortetracycline and sulfapyridine antibiotics on soil enzyme activities. International Agrophysics. 2017;**31**(4):499

[48] Datta R, Baraniya D, Wang YF, Kelkar A, Moulick A, Meena RS, et al. Multi-function role as nutrient and scavenger off reeradical in soil. Sustainability. 2017;**9**:402

[49] Lee MA, Howard-Andrews V, Chester M. Resistance of multiple diploid and tetraploid perennial ryegrass (*Lolium perenne* L.) varieties to three projected drought scenarios for the UK in 2080. Agronomy. 2019;**9**:159. DOI: 10.3390/agronomy9030159

[50] Bothe A, Westermeier P, Wosnitza A, Willner E, Schum A, Dehmer KJ, et al. Drought tolerance in perennial ryegrass (*Lolium perenne* L.) as assessed by two contrasting phenotyping systems. Journal of Agronomy and Crop Science. 2018:1-15. DOI: 10.1111/jac.12269

[51] Thomas H, James AR. Freezing tolerance and solute changes in contrasting genotypes of *Lolium perenne* L. acclimated to cold and drought. Annals of Botany. 1993;**72**:249-254. DOI: 10.1006/anbo.1993.1105

[52] Mohammadi MHS, Etemadi N, Arab MM, Aalifar M, Arab M, Pessarakli M. Molecular and physiological responses of Iranian

perennial ryegrass as affected by trinexapac ethyl, paclobutrazol and abscisic acid under drought stress. Plant Physiology and Biochemistry. 2017;**111**:129-143. DOI: 10.1016/j.plaphy.2016.11.014

[53] Patel M, Milla-Lewis S, Zhang W, Templeton K, Reynolds WC. Over expression of ubiquitin-like *LpHUB1* gene confers drought tolerance in perennial ryegrass. Plant Biotechnology Journal. 2015;**13**:689-699. DOI: 10.1111/pbi.12291

[54] Hu L, Li H, Pang H, Fu J. Responses of antioxidant gene, protein and enzymes to salinity stress in two genotypes of perennial ryegrass (*Lolium perenne*) differing in salt tolerance. Journal of Plant Physiology. 2012;**169**:146-156. DOI: 10.1016/j.jplph.2011.08.020

[55] Norris I. Relationships between growth and measured weather factors among contrasting varieties of *Lolium*, *Dactylis* and *Festuca* species. Grass and Forage Science. 1985;**40**:151-159. DOI: 10.1111/j.1365-2494.1985.tb01732.x

[56] Turner LR, Holloway-Phillips MM, Rawnsley RP, Donaghy DJ, Pembleton KG. The morphological and physiological responses of perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* Schreb.; syn. *Schedonorus phoenix* Scop.) to variable water availability. Grass and Forage Science. 2012;**67**(4):507-518. DOI: 10.1111/j.1365-2494.2012.00866.x

[57] Stiles W, Williams TE. The response of a rye-grass/white clover sward to various irrigation regimes. Journal of Agricultural Science. 1965;**65**:351-364. DOI: 10.1017/S0021859600048917

[58] Van Heeswijck R, McDonald G. *Acremonium endophytes* in perennial ryegrass and other pasture grasses in Australia and New Zealand. Australian Journal of Agricultural Research. 1992;**43**:1683-1709. DOI: 10.1071/ar9921683

[59] Li F, Deng J, Nzabanita C, Li Y, Duan T. Growth and physiological responses of perennial ryegrass to an AMF and an Epichloë endophyte under different soil water contents. Symbiosis. 2019;**75**:151-161. DOI: 10.1007/s13199-019-00633-3

[60] Chen Y, Chen Y, Shi Z, Jin Y, Sun H, Xie FC, et al. Biosynthesis and signal transduction of ABA, JA, and BRs in response to drought stress of Kentucky bluegrass. International Journal of Molecular Sciences. 2019;**20**:1289. DOI: 10.3390/ijms 20061289

[61] Bhatnagar-Mathur P, Vadez V, Sharma KK. Transgenic approaches for abiotic stress tolerance in plants: Retrospect and prospects. Plant Cell Reports. 2008;**27**:411-424. DOI: 10.1007/s00299-007-0474-9

[62] Wehner DJ, Watschke TL. Heat tolerance of Kentucky bluegrasses, perennial ryegrasses, and annual bluegrass. Agronomy Journal. 1981;**73**:79-84. DOI: 10.2134/agronj1981.00021962007300010019x

[63] Harrison J, Tonkinson C, Eagles C, Foyer C. Acclimation to freezing temperatures in perennial ryegrass (*Lolium perenne*). Acta Physiologiae Plantarum. 1997;**19**:505-515. DOI: 10.1007/s11738-997-0047-0

[64] Minner DD, Dernoeden PH, Wehner DJ, Mcintosh MS. Heat tolerance screening of field-grown cultivars of Kentucky bluegrass and perennial ryegrass. Agronomy Journal. 1983;**75**:772-775. DOI: 10.2134/agronj1983.00021962007500050012x

[65] Yang Z, Miao Y, Yu J, Liu J, Huang B. Differential growth and physiological responses to heat stress between two annual and two perennial cool-season

turfgrasses. Scientia Horticulturae. 2014;**170**:75-81. DOI: 10.1016/j.scienta.2014.02.005

[66] Li M, Jannasch AH, Jiang Y. Growth and hormone alterations in response to heat stress in perennial ryegrass accessions differing in heat tolerance. Journal of Plant Growth Regulation. 2019. DOI: 10.1007/s00344-019-10043-w

[67] Kemesyte V, Statkeviciute G, Brazauskas G. Perennial ryegrass yield performance under abiotic stress. Crop Science. 2017;**57**:1935-1940. DOI: 10.2135/cropsci 2016.10.0864

[68] Iwaya-Inoue M, Matsui R, Fukuyama M. Cold- or heat-tolerance of leaves and roots in perennial ryegrass determined by H-NMR. Plant Production Science. 2004;**7**(2):118-128. DOI: 10.1626/pps.7.118

[69] Imada R, Razmjoo K, Hirano J, Kaneko IR. Response of perennial ryegrass (*Lolium perenne* L.) cultivars to heat stress. Japanese Journal of Grassland Science. 1993;**39**(2):225-235

[70] Soliman WS, Fujimori M, Tase K, Sugiyama S. Oxidative stress and physiological damage under prolonged heat stress in C3 grass *Lolium perenne*. Grassland Science. 2011;**57**:101-106. DOI: 10.1111/j.1744-697X.2011.00214.x

[71] Hulke BS, Watkins E, Wyse DL, Ehlke NJ. Freezing tolerance of selected perennial ryegrass (*Lolium perenne* L.) accessions and its association with field winterhardiness and turf traits. Euphytica. 2007;**163**(1):131-141. DOI: 10.1007/s1 0681-007-9631-z

[72] Yang Z, Zhang Z, Zhang T, Fahad S, Cui K, Nie L, et al. The effect of season-long temperature increases on rice cultivars grown in the central and southern regions of China. Frontiers in Plant Science. 2017;**8**:1908. DOI: 10.3389/fpls.2017.01908

[73] Shah F, Lixiao N, Kehui C, Tariq S, Wei W, Chang C, et al. Rice grain yield and component responses to near 2°C of warming. Field Crops Research. 2013;**157**:98-110

[74] Fahad S, Hussain S, Saud S, Hassan S, Chauhan BS, Khan F, et al. Responses of rapid viscoanalyzer profile and other rice grain qualities to exogenously applied plant growth regulators under high day and high night temperatures. PLoS One. 2016;**11**(7):e0159590. DOI: 10.1371/journal.pone.0159590

[75] Fahad S, Hussain S, Saud S, Hassan S, Ihsan Z, Shah AN, et al. Exogenously applied plant growth regulators enhance the morphophysiological growth and yield of rice under high temperature. Frontiers in Plant Science. 2016;**7**:1250. DOI: 10.3389/fpls.2016.01250

[76] Fahad S, Hussain S, Saud S, Hassan S, Tanveer M, Ihsan MZ, et al. A combined application of biochar and phosphorus alleviates heat-induced adversities on physiological, agronomical and quality attributes of rice. Plant Physiology and Biochemistry. 2016;**103**:191-198

[77] Fahad S, Hussain S, Saud S, Khan F, Hassan S, Jr A, et al. Exogenously applied plant growth regulators affect heat-stressed rice pollens. Journal of Agronomy and Crop Science. 2016;**202**:139-150

[78] Fahad S, Hussain S, Saud S, Tanveer M, Bajwa AA, Hassan S, et al. A biochar application protects rice pollen from high-temperature stress. Plant Physiology and Biochemistry. 2015;**96**:281-287

[79] Fahad S, Muhammad ZI, Abdul K, Ihsanullah D, Saud S, Saleh A, et al. Consequences of high temperature under changing climate optima for rice pollen characteristics-concepts

and perspectives. Archives of Agronomy and Soil Science. 2018. DOI: 10.1080/03650340.2018.1443213

[80] Fahad S, Adnan M, Hassan S, Saud S, Hussain S, Wu C, et al. Rice responses and tolerance to high temperature. In: Hasanuzzaman M, Fujita M, Nahar K, Biswas JK, editors. Advances in Rice Research for Abiotic Stress Tolerance. Cambridge, England: Woodhead Publ Ltd; 2019. pp. 201-224

[81] Pociecha E, Jurczyk B, Dziurka M, Paczyński R, Okleštková J, Janeczko A. 24-epibrassinolide promotes carbohydrates accumulation in crowns of perennial ryegrass during cold acclimation by regulation of gene expression and enzyme activities which results in increased frost tolerance. Procedia Environmental Sciences. 2015;**29**:234-235. DOI: 10.1016/j.proenv.2015.07.289

[82] Hoffman L, DaCostaa M, Ebdon JS, Zhao J. Effects of drought preconditioning on freezing tolerance of perennial ryegrass. Environmental and Experimental Botany. 2012;**79**:11-20. DOI: 10.1016/j.envexpbot.2012.01.002

[83] Krasensky J, Jonak C. Drought, salt, and temperature stress-induced metabolic rearrangements and regulatory networks. Journal of Experimental Botany. 2012;**63**:1593-1608. DOI: 10.1093/jxb/err460

[84] Du H, Zhou P, Huang B. Antioxidant enzymatic activities and gene expression associated with heat tolerance in a cool-season perennial grass species. Environmental and Experimental Botany. 2013;**87**:159-166. DOI: 10.1016/j.envexpbot.2012.09.009

[85] Wang J, Zhuang L, Zhang J, Yu J, Yang Z, Huang B. Identification and characterization of novel homeodomain leucine zipper (HD-Zip) transcription factors associated with heat tolerance in perennial ryegrass. Environmental and Experimental Botany. 2019;**160**:1-11. DOI: 10.1016/j.envexpbot.2018.12.023

[86] Dai Y, Mao P, Tao X, Wang Y, Wei C, Ma X. Flexible shift on gene body methylation and transcription of *LpCYP72A161* exposed to temperature stress in perennial ryegrass. Environmental and Experimental Botany. 2017;**143**:29-37. DOI: 10.1016/j.envexpbot.2017.08.002

[87] Fahad S, Bano A. Effect of salicylic acid on physiological and biochemical characterization of maize grown in saline area. Pakistan Journal of Botany. 2012;**44**:1433-1438

[88] Fahad S, Hussain S, Matloob A, Khan FA, Khaliq A, Saud S, et al. Phytohormones and plant responses to salinity stress: A review. Plant Growth Regulation. 2014b;**75**(2):391-404. DOI: 10.1007/s10725-014-0013-y

[89] Hu T, Li H, Zhang X, Luo H, Fu J. Toxic effect of NaCl on ion metabolism, antioxidative enzymes and gene expression of perennial ryegrass. Ecotoxicology and Environmental Safety. 2011;**74**:2050-2056. DOI: 10.1016/j.ecoenv.2011.07.013

[90] Hu T, Zhang XZ, Sun JM, Li HY, Fu JM. Leaf functional trait variation associated with salt tolerance in perennial ryegrass. Plant Biology. 2014;**16**:107-116. DOI: 10.1111/plb.12012

[91] Hu T, Jin Y, Li H, Amombo E, Fu J. Stress memory induced transcriptional and metabolic changes of perennial ryegrass (*Lolium perenne*) in response to salt stress. Physiologia Plantarum. 2016;**156**:54-69. DOI: 10.1111/ppl.12342

[92] Pompeiano A, Patrizio ED, Volterrani M, Scartazza A, Guglielminetti L. Growth responses and physiological traits of seashore subjected to short-term salinity stress and recovery. Agricultural Water Management. 2016;**163**:57-65. DOI: 10.1016/j.agwat.2015.09.004

[93] Li X, Han S, Wang G, Liu X, Amombo E, Xie Y, et al. The fungus *Aspergillus aculeatus* enhances salt-stress tolerance, metabolite accumulation, and improves forage quality in perennial ryegrass. Frontiers in Microbiology. 2017;**8**:1664. DOI: 10.3389/fmicb.2017.01664

[94] Wu Y, Chen Q, Chen M, Chen J, Wang X. Salt-tolerant transgenic perennial ryegrass (*Lolium perenne* L.) obtained by *Agrobacterium tumefaciens*-mediated transformation of the vacuolar Na^+/H^+ antiporter gene. Plant Science. 2005;**169**(1):65-73. DOI: 10.1016/j.plantsci.2005.02.030

[95] He A, Niu S, Zhao Q, Li Y, Gou J, Gao H. Induced salt tolerance of perennial ryegrass by a novel bacterium strain from the rhizosphere of a desert shrub *Haloxylon ammodendron*. International Journal of Molecular Sciences. 2018;**19**:469. DOI: 10.3390/ijms19020469

[96] Fahad S, Rehman A, Shahzad B, Tanveer M, Saud S, Kamran M, et al. Rice responses and tolerance to metal/metalloid toxicity. In: Hasanuzzaman M, Fujita M, Nahar K, Biswas JK, editors. Advances in Rice Research for Abiotic Stress Tolerance. Cambridge, England: Woodhead Publ Ltd; 2019. pp. 299-312

[97] Qamar-uz Z, Zubair A, Muhammad Y, Muhammad ZI, Abdul K, Fahad S, et al. Zinc biofortification in rice: Leveraging agriculture to moderate hidden hunger in developing countries. Archives of Agronomy and Soil Science. 2017;**64**:147-161. DOI: 10.1080/03650340.2017.1338343

[98] Frossard R, Stadelmann FX, Niederhauser J. Effects of different heavy metals on fructan, sugar and starch content of ryegrass. Journal of Plant Physiology. 1989;**134**:180-185. DOI: 10.1016/s0176-1617(89)80052-5

[99] Li F, Qiu Y, Xu X, Yang F, Wang Z, Feng J, et al. EDTA-enhanced phytoremediation of heavy metals from sludge soil by Italian ryegrass (*Lolium perenne* L.). Ecotoxicology and Environmental Safety. 2020;**191**:110185. DOI: 10.1016/j.ecoenv.2020.110185

[100] Norini M, Thouin H, Miard F, Battaglia-Brunet F, Gautret P, Guégan R, et al. Mobility of Pb, Zn, Ba, As and Cd toward soil pore water and plants (willow and ryegrass) from a mine soil amended with biochar. Journal of Environmental Management. 2019;**232**:117-130. DOI: 10.1016/j.jenvman.2018.11.021

[101] Zhao S, Liu Q, Qi Y, Duo L. Responses of root growth and protective enzymes to copper stress in turfgrass. Acta Biologica Cracoviensia Series Botanica. 2010;**52**:7-11. DOI: 10.2478/v10182-010-0017-5

[102] Berríos GA, Escobar AL, Alberdi MR, Nunes-Nesi A, Reyes-Díaz MM. Manganese toxicity amelioration by phosphorus supply in contrasting Mn resistant genotypes of ryegrass. Plant Physiology and Biochemistry. 2019;**144**:144-156. DOI: 10.1016/j.plaphy.2019.09.034

[103] Hu Y, Habibul N, Hu Y, Meng F, Zhang X, Sheng G. Mixture toxicity and uptake of 1-butyl-3-methylimidazolium bromide and cadmium co-contaminants in water by perennial ryegrass (*Lolium perenne* L.). Journal of Hazardous Materials. 2020;**386**:121972. DOI: 10.1016/j.jhazmat.2019.121972

[104] Bennet J, Stewart A. The aluminium response network in perennial ryegrass (*Lolium perenne*): II. Water fluxes and ion transport. South African Journal of Plant and Soil. 1999;**16**(1):1-9. DOI: 10.1080/02571862.1999.10634837

[105] Jia H, Hou D, Connor DO, Pan S, Zhu J, Bolan NS, et al. Exogenous

phosphorus treatment facilitates chelation-mediated cadmium detoxification in perennial ryegrass (*Lolium perenne* L.). Journal of Hazardous Materials. 2020;**389**:121849. DOI: 10.1016/j.jhazmat.2019.121849

[106] Luo H, Li H, Zhang X, Fu J. Antioxidant responses and gene expression in perennial ryegrass (*Lolium perenne* L.) under cadmium stress. Ecotoxicology. 2011;**20**:770-778. DOI: 10.1007/s10646-011-0628-y

[107] Hua L, Wang Y, Wu W, McBride MB, Chen Y. Biomass and Cu and Zn uptake of two turfgrass species grown in sludge compost–soil mixtures. Water, Air, and Soil Pollution. 2008;**188**:225-234. DOI: 10.1007/s11270-007-9539-1

[108] Taghizadeh M, Solgi E. Impact of heavy metal stress on in vitro seed germination and seedling growth indices of two turfgrass species. Journal of Rangeland Science. 2017;**7**:220-231

[109] Lou Y, Yang Y, Hu L, Liu H, Xu Q. Exogenous glycinebetaine alleviates the detrimental effect of Cd stress on perennial ryegrass. Ecotoxicology. 2015;**24**:1330-1340. DOI: 10.1007/s10646-015-1508-7

[110] Dong Y, Xu L, Wang Q, Fan Z, Kong J, Bai X. Effects of exogenous nitric oxide on photosynthesis, antioxidative ability, and mineral element contents of perennial ryegrass under copper stress. Journal of Plant Interactions. 2014;**9**:402-411. DOI: 10.1080/17429145.2013.845917

[111] Duo LA, Lian F, Zhao SL. Enhanced uptake of heavy metals in municipal solid waste compost by turfgrass following the application of EDTA. Environmental Monitoring and Assessment. 2010;**165**:377-387. DOI: 10.1007/s10661-009-0953-2

[112] Zhao S, Lian F, Duo L. EDTA-assisted phytoextraction of heavy metals by turfgrass from municipal solid waste compost using permeable barriers and associated potential leaching risk. Bioresource Technology. 2011;**102**:621-626. DOI: 10.1016/j.biortech.2010.08.006